Performance Analysis of an OFDM Based Optical Wireless Communication Impaired by Backscattering

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Abstract

Optical wireless communication (OWC) is increasingly becoming an intrinsic part of modern life. Orthogonal frequency division multiplexing (OFDM) is rapidly gaining popularity as a high data rate transmission. Therefore, the integration of the two technologies has the potential to meet the ever growing demands of future optical wireless communication system. OFDM based OWC suffer from various impairments such as backscattering, frequency offset and phase noise. A mathematical model for OFDM-OWC system has been developed in the present study. Numerical results are provided to evaluate the error performance of OFDM-OWC system with the presence of backscattering, frequency offset and phase noise. There is significant deterioration in bit error rate (BER) performance due to the above mention system imperfection. We have to propose a ICI cancellation method to reduce received power that is 2.5 – 3 dBm.

Keywords

Atmospheric Scintillation; Backscattering; Frequency Offset; Orthogonal Frequency Division Multiplexing (OFDM); Optical Wireless Communication (OWC) and Phase Noise

Introduction

Optical wireless communication (OWC) is an up-and-coming technology and an efficient utilization of communication resource. OWC has potential applications in outdoor as well as indoor terrestrial applications [1, 2]. The main advantages of an OWC are enormous amount of unregulated bandwidth, no license requirement, low cost transceivers and no interference with sensitive electronic system [3, 4].

Orthogonal frequency division multiplexing (OFDM) is a suitable modulation scheme for OWC which offers high data rate, high bandwidth efficiency, receiver sensitivity and robustness against polarization dispersion [5, 6]. However, subcarrier frequency offset and phase noises have been recognized as two major drawbacks of OFDM. Both frequency offset and phase noise lead to inter carrier interference (ICI). For ICI, the performance of OFDM can severely be affected and degrade the BER of the system.

Atmospheric scintillation, scattering and backscattering degrade the performance of OFDM-OWC. The effect of crosstalk due to backscattered light is one of the numbers of interferences that degrade the signal [7]. Debbie Kedar *et al.* (2005) have investigated the crosstalk effect of aerosol backscattering on the performance of a wavelength division multiplexed (WDM) OWC system [7].

In this paper an illustrative analytical model for the performance evaluation of intensity modulation and direct detection (IM/DD) OFDM-OWC scheme is derived considering the effect of backscattered light, frequency offset and phase noise. The performance analysis is based on the bit error rate (BER). Performance degradation due to backscattered light, frequency offset and phase noise are numerically evaluated at 500 MHz bandwidth. We have also discussed a theoretical analysis of ICI cancellation and to evaluate in MATLAB.

System Model

The system model of the OFDM based OWC is shown in fig. 1. The input data are modulated using OFDM modulation technique. After digital to analogue conversion, intensity modulation is conducted to OFDM data by the laser transmitter and then the output optical collimated beam is transmitted towards the receiver. The transmitted OFDM signal at the transmitter could be expressed as [8],

$$s(n) = \sum_{k=0}^{N-1} d_k e^{j(\frac{2\pi}{N})kn} \quad \text{for } 0 \le n \le N\text{-}1 \qquad (1)$$

Where, j = $\sqrt{-1}$, N is the total number of subcarriers, d_k is data symbol over the k[th] subcarrier. At the receiver, the received optical signal is collimated to a beam and fed to photodiode which convert electrical signal. Then OFDM signal is converted to digital form. Received signal is affected by phase noise and frequency offset. So, it can be expressed as [8],

$$r(n) = [s(n) \otimes h(n) + w(n)]e^{j[2\pi\Delta ft + \phi(n)]} \quad (2)$$

Where, Δf and $\phi(n)$ are frequency offset and phase noise. $s(n)$, $h(n)$, $w(n)$, $r(n)$ are transmitted signal, channel impulse response, complex Additive White Gaussian Noise (AWGN) and received signal respectively. The received signal can be expressed as [8],

$$\begin{aligned} Y(k) &= \frac{1}{N}\sum_{n=0}^{N-1} r(n)e^{-j[\frac{2\pi}{N}]kn} \\ &= \frac{1}{N}\sum_{n=0}^{N-1}\sum_{l=0}^{N-1} d_l H_l e^{j[(\frac{2\pi}{N})(l-k+\varepsilon)n+\phi(n)]} + N_k \\ &= \sum_{l=0}^{N-1} d_l H_l Q_{l-k} + N_k \end{aligned} \quad (3)$$

Where, $Y(k)$, d_l and H_l are the frequency domain expression of $r(n)$, $d(n)$, $h(n)$. N_k is the complex AWGN. Here, ε is the normalized frequency offset and is given by ΔfT. Δf is the frequency difference between the transmitted and received carrier frequencies and T is the subcarrier symbol period. Q_L^r is defined as follows [8],

$$\begin{aligned} Q_L &= \frac{1}{N}\sum_{n=0}^{N-1} e^{j[(\frac{2\pi}{N})(L+\varepsilon)n+\phi(n)]} \\ &= \exp[\{j2\pi(L+\varepsilon)+\phi\}(1/2-1/2N)]\frac{\sin\{2\pi(L+\varepsilon)+\phi\}/2]}{N.\sin[\{2\pi(L+\varepsilon)+\phi\}/2N]} \end{aligned} \quad (4)$$

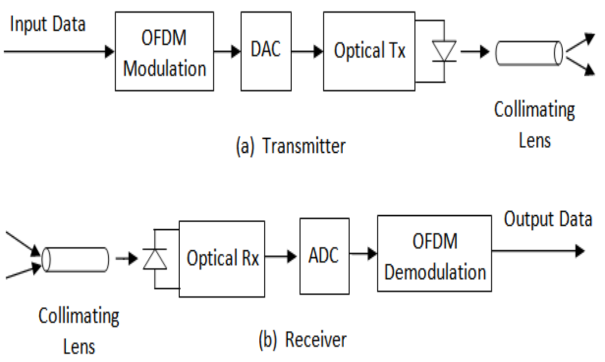

FIG. 1 OFDM BASED OWC SCHEME (a) TRANSMITTER (b) RECEIVER

Frequency offset and random phase noise signal of OFDM-OWC signal become corrupted at the receiving end. It involves two kinds of components. One component is its own subcarrier signal corrupted by common phase error and the other is ICI from adjacent subcarrier signals. Here, the cyclic prefix is not considered for the ease of analysis.

At the receiver, photo detector is used, which can be modeled as the square law detector, so the resultant photocurrent is [9],

$$\begin{aligned} I \propto |y(k)|^2 &= \eta|y(k)|^2 \\ &= \eta I_{signal}^2 + \eta\sigma_{ICI}^2 + N_k \end{aligned} \quad (5)$$

Where, η is photodiode efficiency. The average received current from the signal and the backscattered interference are I_{signal} and I_{BS} respectively. In order to evaluate the statistical properties [10], assuming average channel gain

$$E\left[|H_l|^2\right] = 1 \text{ and } E\left[|d_l|^2\right] = |d|^2 \quad (6)$$

The received signal is generated by the signal of k[th] subcarrier. Considering $l=k$, the received signal power can be represented by

$$I_{signal}^2 = E[|d_k|^2].E[|H_k|^2].|Q_0|^2 = |d_k|^2.|H_k|^2.|Q_0|^2 \quad (7)$$

ICI is corrupted by adjacent subcarrier signal. Considering $l \neq k$, the ICI power is

$$\begin{aligned} \sigma_{ICI}^2 &= \sum_{l=0,l\neq k}^{N-1} E[|d_l|^2].E[|H_l|^2].|Q_{l-k}|^2 \\ &= \sum_{l=1}^{N-1}|d_l|^2.|H_l|^2.|Q_l|^2 \end{aligned} \quad (8)$$

The noise terms are $\sigma_{ASE\times ASE}^2$, $\sigma_{ASE\times S}^2$ and $\sigma_{ASE\times BS}^2$ due to beating of the amplified spontaneous emission (ASE) from the optical amplifier with itself, the signal and the backscatter respectively. $\sigma_{S\times BS}^2$ is the noise due to the mixing of the signal with the backscatter. The beat noise terms caused by the mixing of two signals can be defined as [11]

$$\sigma_{ASE\times ASE}^2 = [q\eta GF_n]^2 \Delta\upsilon B \quad (9)$$

$$\sigma_{ASE\times S}^2 = \frac{2F_n}{h\upsilon}[q\eta G]^2 P_R B \quad (10)$$

$$\sigma_{ASE\times BS}^2 = \frac{2F_n}{h\upsilon}[q\eta G]^2 P_{BS} B \quad (11)$$

$$\sigma_{S\times BS}^2 = \frac{1}{\sqrt{2}}(\frac{q\eta G}{h\upsilon})^2 P_R P_{BS} \quad (12)$$

where, q , h , υ , B, G , F_n are the electron charge, Planck's constant, optical frequency of the received power, electronic bandwidth, optical amplifier gain and noise factor. Here backscatter is denoted as 'BS'. P_R and P_{BS} are the received power and backscatter power. I_D is the threshold current which is represented by $(I_{signal} + I_{BS})/2$. Hence, the noise current variances are given by [11]

$$\sigma_{10}^2 = \sigma_{ASE\times ASE}^2 + \sigma_{ASE\times S}^2 = (q\eta G)^2 BF_n\left[\Delta\upsilon F_n + \frac{2P_R}{h\upsilon}\right] \quad (13)$$

$$\sigma_{01}^2 = \sigma_{ASE\times ASE}^2 + \sigma_{ASE\times BS}^2 = (q\eta G)^2 BF_n\left[\Delta\upsilon F_n + \frac{2P_{BS}}{h\upsilon}\right] \quad (14)$$

$$\sigma_{11}^2 = \sigma_{ASE\times ASE}^2 + \sigma_{ASE\times S}^2 + \sigma_{ASE\times BS}^2 + \sigma_{S\times BS}^2$$
$$= (q\eta G)^2\left[B\Delta\upsilon(F_n)^2 + \frac{2BF_n(P_R+P_{BS})}{h\upsilon} + \frac{1}{\sqrt{2}}.\frac{P_RP_{BS}}{(h\upsilon)^2}\right] \quad (15)$$

$$\sigma_{00}^2 = \sigma_{ASE\times ASE}^2 = [q\eta GF_n]^2\Delta\upsilon B \quad (16)$$

BER of OFDM based optical wireless communication can be expressed as,

$$BER = 0.25.erfc\left(\frac{I_{signal}-I_D}{\sqrt{2}\{\sigma_{10}^2+\sigma_{ICI}^2\}^{0.5}}\right) + 0.25.erfc\left(\frac{I_{signal}+I_{BS}-I_D}{\sqrt{2}\{\sigma_{11}^2+\sigma_{ICI}^2\}^{0.5}}\right)$$
$$+0.25.erfc\left(\frac{I_D-I_{BS}}{\sqrt{2}\{\sigma_{01}^2+\sigma_{ICI}^2\}^{0.5}}\right) + 0.25.erfc\left(\frac{I_D}{\sqrt{2}\{\sigma_{00}^2+\sigma_{ICI}^2\}^{0.5}}\right) \quad (17)$$

Now we have to arrange a data to the following,

$$d_1 = -d_0, d_3 = -d_2, \ldots\ldots, d_{N-1} = -d_{N-2} \quad (18)$$

At the receiver, the equation (3) can be revised as,

$$Y(k) = \sum_{l=0,2,4\ldots}^{N-1} d_l H_l Q_{l-k} + \sum_{l=1,3,5\ldots}^{N-2} d_l H_l Q_{l-k} + N_k$$
$$= \sum_{l=0,1,2\ldots}^{N/2-1} d_{2l}H_{2l}Q_{2l-k} + \sum_{l=0,1,2\ldots}^{N/2-1} d_{2l+1}H_{2l+1}Q_{2l+1-k} + N_k$$
$$= \sum_{l=0,1,2\ldots}^{N/2-1} d_{2l}H_{2l}Q_{2l-k} - d_{2l+1}H_{2l+1}Q_{2l+1-k} + N_k \quad (19)$$

From the equation (19), ICI cancellation coefficient can be defined as,

$$Q_{2l-k} = Q_{2l-k} - Q_{2l+1-k} \quad (20)$$

In this scheme, we have to transmit half data. Original data is transmitted to the odd subcarrier. Negative data is transmitted to the even subcarrier. ICI coefficient revokes the frequency offset and phase noise to minus the two neighbor subcarrier.

Results and Discussion

The theoretical analysis has so far evaluated the bit error rate performance results of OFDM-OWC with IM/DD system. The Values of System Parameters are given in table 1.

TABLE-1 VALUES OF SYSTEM PARAMETERS

Parameter	Typical value
Electronic Bandwidth, B	500 (MHz)
Amplifier Gain, G	1000 (30 dB)
Noise Figure, F_n	2.238 (4 dB)
Photodiode Efficiency, η	0.8
Optic Frequency (central), υ	1.94×10^{14} (Hz)
Optic Bandwidth, Δ υ	125 (GHz)

The plots of BER versus received optical power (dBm) are shown in fig. 2 for an OFDM-OWC in the presence of backscattered optical power (P_{BS}). The results show that BER performance improves with increased received power for a specified value of P_{BS}. However, there is degradation in BER performance in the presence of backscattering. The degradation in BER is significant at higher values of P_{BS}.

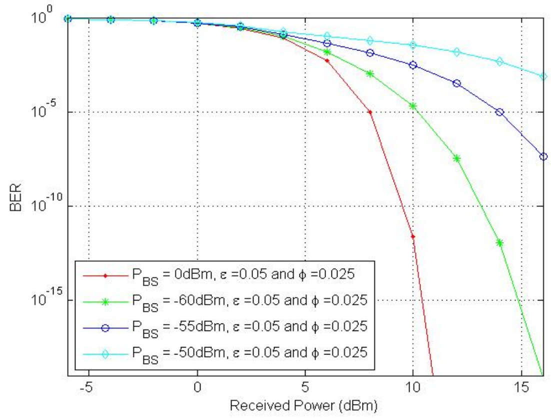

FIG. 2 BER VS RECEIVED POWER WITH DIFFERENT BACKSCATTERING OPTICAL POWER

Fig. 3 depicts the effect of normalized frequency offset on the BER performance at constant phase noise. In this figure, there is no backscattered power. It is noticed that the system performance degradation occurs increasing values of the normalized frequency offset. The degradation is significant at increased value of ε. For a value of 6dBm received power, the BER is approximately $9.7x10^{-8}$ at ε = 0.025 and $5.2x10^{-3}$ at ε = 0.05 respectively.

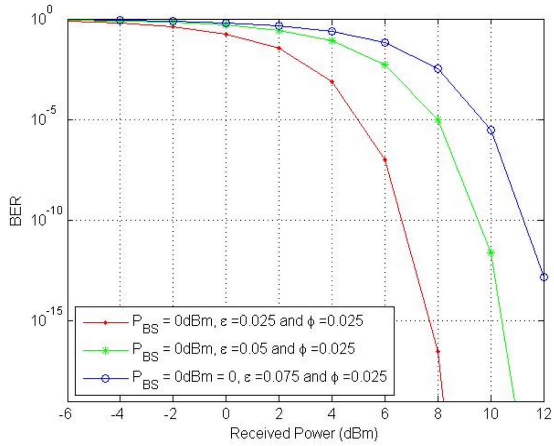

FIG. 3 BER VS RECEIVED POWER WITH DIFFERENT NORMALIZED FREQUENCY OFFSET

In the presence of phase noise, the BER performance results are shown in fig. 4 as a function of received optical power with constant normalized frequency offset. There is deterioration in BER performance compared to that of fig. 3. It is clearly noticed that the

amount of BER performance degrades due to phase noise. For example, the BER is approximately $9.7x10^{-8}$ (ϕ =0.025) and $3.01x10^{-6}$ (ϕ = 0.05) at the same value of received power respectively.

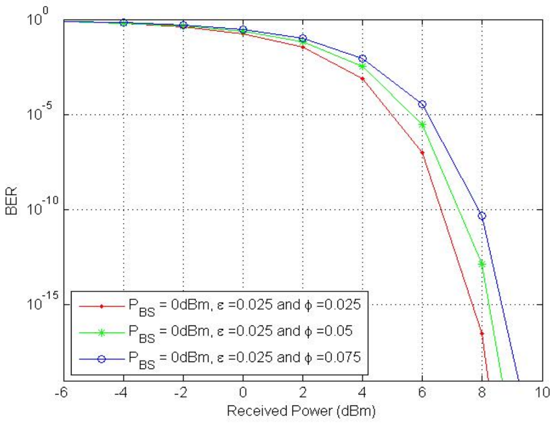

FIG. 4: BER VS RECEIVED POWER WITH DIFFERENT PHASE NOISE

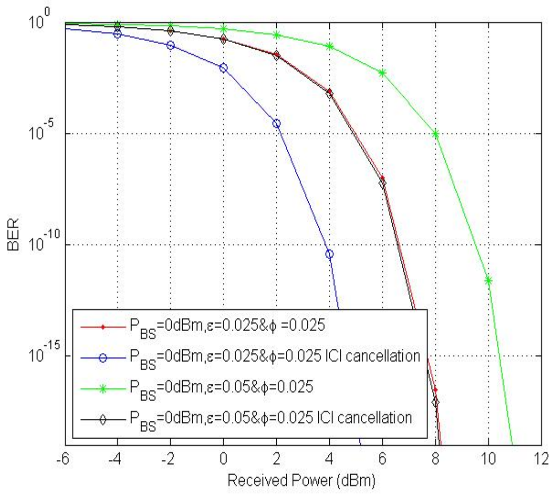

FIG. 5 BER VS RECEIVED POWER WITH NORMALIZED FREQUENCY OFFSET & ICI CANCELLATION

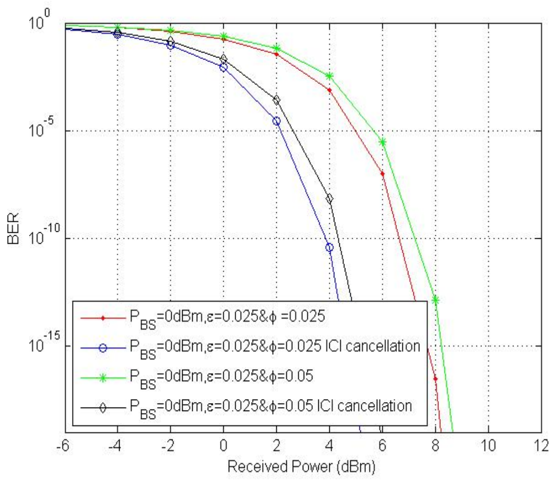

FIG. 6 BER VS RECEIVED POWER WITH DIFFERENT PHASE NOISE & ICI CANCELLATION

Fig. 5 shows the performance of ICI cancellation technique. The proposed scheme can achieve 2.5-3 dBm more improvement in the received power at BER= 10^{-10}. It is also demonstrated in Fig. 6 that the proposed scheme can significantly reduce received power which is 2.5-3 dBm at BER= 10^{-10}.

Conclusion

In the present study, a theoretical analysis of OFDM based OWC has been discussed and the effect of channel impairments like backscattering, frequency offset and phase noise has been tried to find out. It is observed that that backscattering is too high while the BER is large. Small variations of the frequency offset and phase noise have a significant effect on the BER performance. We also reduce ICI in our proposed scheme. OFDM-OWC transmission scheme is reliable, when channel impairments are eliminated.

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